(NASA-CR-126310) LIMITS ON INTERGALACTIC HELIUM FROM THE 3C 273 X-RAY SPECTRUM B. Margon, et al (California Univ.) Feb. 1972 14 p CSCL 03B

N72-22808

Unclas G3/30 15430

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by

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NASA Grant NGR 05-003-278

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Space Sciences Laboratory Series 13 Issue 2

UNIVERSITY OF CALIFORNIA, BERKELEY

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This work was supported by NASA Grant
NGR 05-003-278 and has been accepted
for publication in The Astrophysical Journal.

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ABSTRACT: An X-ray spectrum of the quasi-stellar object 3C 273 in the interval 0.25 to 10 keV has been obtained by sounding rocket observations. The best-fit power law spectrum has photon index n= 1.3 with no photoelectric absorption. An upper limit on the X-ray optical depth to 3C 273 has been calculated from the data, permitting upper limits to be set on the absolute abundance of helium in the intergalactic medium.

I. INTRODUCTION

Several techniques have been applied to place upper limits on the density of the intergalactic medium (IGM). The search for red-shifted Lyman-alpha absorption against the continuum spectrum of a quasi-stellar object (Scheuer, 1965; Gunn and Peterson, 1965) is by far the most sensitive test for neutral hydrogen and provides an upper limit of $\approx 10^{-13}$ atoms cm^{-3} (Burbidge and Burbidge, 1967) for the local density of hydrogen in the IGM. This observation can also be used to set stringent upper limits on the intergalactic abundance of heavy elements such as LiI, CI, OI, and FeI (Bahcall and Salpeter, 1965). Cowsik (1971) has shown that if the break near 40 keV in the diffuse X-ray background is due to thermal emission from an IGM at 10^8 °K, the relative abundance of iron in this medium must be at least a factor of 200 below that observed in the Galaxy.

The technique discussed by Bahcall and Salpeter (1965) may also be used to limit the intergalactic abundance of HeI and HeII if these elements are in their first excited states. However, it does not seem likely that this condition is satisfied. Thus no technique yet applied yields any direct information on intergalactic helium abundance. Theoretically, we should expect the heavy element abundance to be quite small (Wagoner, Fowler, and Hoyle, 1967); however, the absolute abundance of helium may certainly be nontrivial. Photoionization of helium may be important in the thermal history and balance of the IGM (Arons and McCray, 1969). In addition, the question of the relative abundance of helium to hydrogen in the IGM is of crucial cosmological significance.

It has been suggested (Rees, Sciama, and Setti, 1968; Rees and Setti,

1970) that the IGM may be probed by searching for photoelectric absorption in the spectrum of the diffuse X-ray background. This is a potentially sensitive test for helium, since it has a photoelectric absorption cross section which substantially exceeds that of hydrogen. However, present observations of the X-ray background in the region 0.28 keV are quite discrepant (Silk, 1970), and both the intrinsic spectrum and the absolute intensity of the radiation are uncertain. It is therefore difficult at this time to use this method to derive quantitative information on the X-ray optical depth due to the IGM. An alternate technique (Rees et al., 1968; Silk, 1971) is to search for photoelectric absorption in the continuous spectra of distant discrete X-ray sources. We report here the first results derived from this technique, using an X-ray spectrum of the quasi-stellar object 3C 273.

II. EXPERIMENTAL DATA

A complete report of the experiment detecting X-ray emission from 3C 273 has appeared previously (Bowyer et al., 1970). The source was detected independently by two rocket-borne argon-methane proportional counters equipped with Mylar windows. One detector, equipped with a $3° \times 12°$ FWHM fan beam collimator, observed the source for 19 sec; the other, collimated with a 1.6° FWHM pencil beam, observed the source for approximately 10 sec. The spectrum reported here was derived solely from data from the pencil beam detector, whose small solid angle of 7×10^{-4} sterad causes it to be insensitive to the diffuse X-ray background. The chief source of background in this detector was due to unrejected cosmic-ray events; this background level was set using 50 sec of high-latitude data which excluded the positions of all known X-ray sources. The intensity derived for 3C 273, 0.160 ± 0.055 keV cm^{-2} sec^{-1} in the interval 1 to 10 keV, agrees well with that reported by the UHURU satellite (Kellogg et al., 1971), thus lending further confidence to the background subtraction procedure.

In Figure 1 we present the X-ray spectrum of 3C 273, derived from the central 8.32 sec of the transit of the source through the detector. Each experimental point has been corrected for background, detector efficiency, energy resolution, and argon escape radiation. We have fitted the experimental data to a power law spectrum of photon index n, subjected to photoelectric absorption with optical depth τ, through the relation

$$F(E) = cE^{-n} \exp(-\tau) \text{ photons cm}^{-2} \text{ sec}^{-1} \text{ keV}^{-1} ,$$

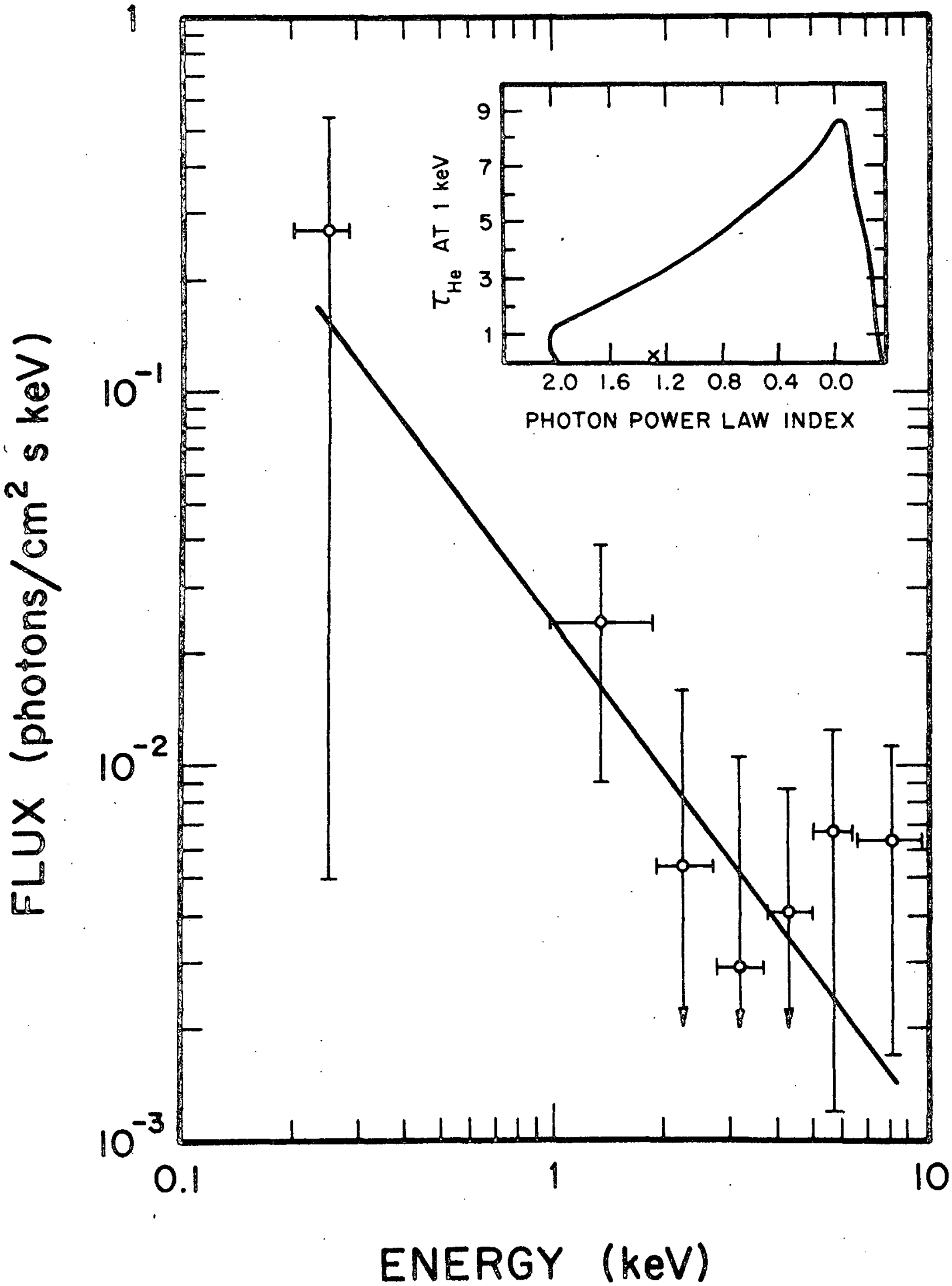

Figure 1. X-ray spectrum of 3C273. Error bars are ±1 σ statistical errors. Solid line: best power-law fit to the data. Inset: contour of constant probability for the least-squares fitting procedure. The cross marks the highest confidence model.

where $\tau = N\sigma$ and N and σ are respectively the column density and the photoelectric absorption cross section of helium. In this analysis, c, N, and n have been permitted to vary as free parameters. The details of the least-squares fitting procedure have appeared previously (Lampton et al., 1971). The best-fitting spectrum, $F(E) = 0.028\ E^{-1.3}$ photons $cm^{-2}\ sec^{-1}\ keV^{-1}$, is shown by the solid line in Figure 1. This spectrum has a confidence of 71% and shows no evidence for photoelectric absorption ($\tau = 0$). The inset to Figure 1 presents a contour of constant probability for the least-squares fits; the contour displayed is where the confidence drops to $e^{-0.5} = 0.607$ of the peak value, which is analagous to the standard deviation of a Gaussian variate.

III. ANALYSIS AND DISCUSSION

Few assumptions need be made to derive an upper limit on the helium abundance in the IGM from these data. We must assume that 3C 273 is at the cosmological distance indicated by its redshift of 0.158. This object is then the most distant known X-ray source, at a distance of 580 Mpc, assuming a Hubble constant of $H_0 = 75$ km sec^{-1} Mpc^{-1} (Sandage, 1968).

Upper limits on the absolute helium abundance in the IGM can be set independent of the relative abundance of helium by assuming that all of the maximum permitted optical depth in the X-ray spectrum is due to helium. This is a reasonable assumption in any case, since at 1 keV the HeI cross section is a factor of ≈ 30 greater than that of HI. We may neglect absorbing matter within our own Galaxy, as 21-cm absorption studies against 3C 273 (Williams, 1965; Hughes, Thomson, and Colvin, 1971; Radhakrishnan et al., 1971) show that at 1 keV, $\tau \lesssim 0.02$ for assumed abundances of the interstellar medium (Brown and Gould, 1970).

We may avoid assumptions on the ionization mechanism and equilibrium of intergalactic helium by obtaining separate limits for HeI and HeII. Following Silk (1971), we calculate the density of intergalactic helium, ρ_{He}, from the relation

$$\rho_{He} = \frac{\tau_1\ H_0\ m_{He}}{\sigma c G(z)} \qquad \text{gm cm}^{-3} ,$$

where

$$G(z) = \int_0^z \frac{dz}{(1+z)^2\,(1+\Omega z)^{\frac{1}{2}}} \approx \frac{z}{1+z} \quad (\Omega z < < 1).$$

In these expressions, $\Omega = \rho/\rho_{crit}$, σ is the cross section at 1 keV for HeI (Henke, 1967) or HeII (Brown and Gould, 1970), and τ_1 is the observed upper limit on the optical depth at 1 keV.

The probability contour in Figure 1 permits us to conclude that the maximum optical depth at 1 keV compatible with the observational data is $\tau_1 = 8.7$. We note that if we use this "worst-case" optical depth, the value of τ_1 is independent of the true value of the photon power law index n. In this analysis we have assumed that the spectrum of 3C 273 is in fact a power law within the energy range of our observations. This assumption appears justified for a number of reasons. First, our spectral data may be fitted by this model with satisfactory confidence. Second, most X-ray emission mechanisms proposed for quasi-stellar objects, involving synchrotron radiation or the inverse Compton effect, result in power-law spectra in the keV regime. Third, all other reported extragalactic X-ray spectra of sources in which violent events are occuring, M87 (Lampton et al., 1971 and references therein), NGC 5128 (Lampton et al., 1972), and NGC 1275 (Fritz et al., 1971), are compatible with power laws. Since these spectra are also compatible with thermal bremsstrahlung emission mechanisms, however, we have also compared our data with an exponential spectrum. We find that all source temperatures $T \gtrsim 1.5 \times 10^7$ °K are compatible with the observations at the 1σ level, and the maximum permitted optical depth at 1 keV is $\tau_1 = 3.2$. Thus if we utilize the larger value of τ_1 derived for power law spectra, we are assured of calculating valid upper limits on abundances even if the observed X-rays are due to thermal bremsstrahlung.

In Figure 2 we present the results so derived for helium. Since the distance to the source as well as the critical density of the IGM depends upon the uncertain value of H_0, we have performed the calculations for a range of likely values of this parameter. The figure also indicates the density of matter necessary to close a Friedmann Universe at each value of H_0. For favorable values of H_0, the present upper limits are a factor of about 8 greater than the critical density. These

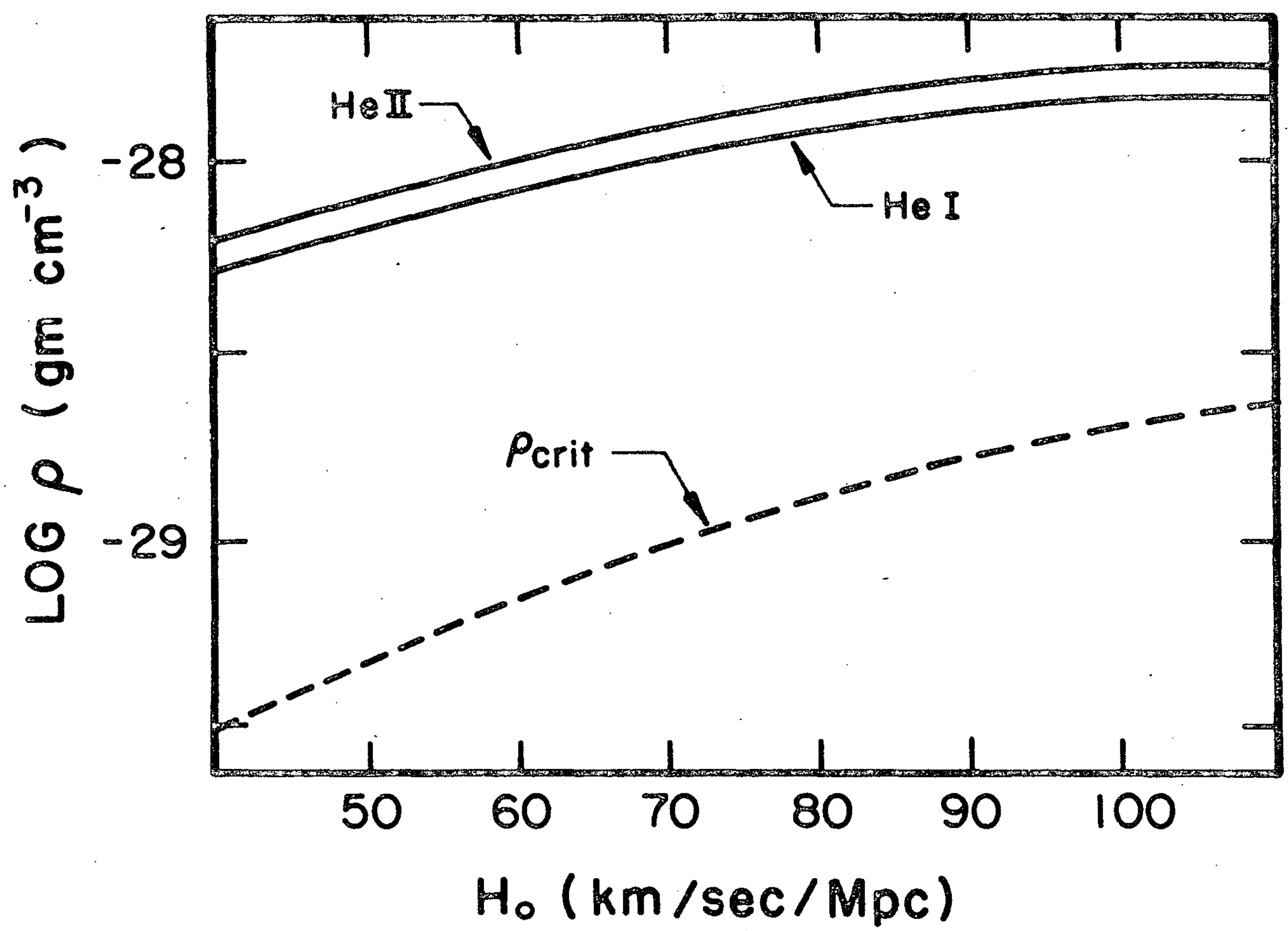

Figure 2. Solid lines: upper limits on helium abundance in the intergalactic medium as a function of the Hubble constant. Broken lines: critical densities for a Friedmann Universe.

limits are quite crude due to the short time that the source was observed and the resulting uncertainty in τ_1. However, increased exposures obtainable even with current rocket-borne instrumentation can set stringent limits on helium in the IGM.

Another X-ray source to which this technique may be applicable is NGC 1275 (Fritz et al., 1971; Gursky et al., 1971). At a distance of approximately 70 Mpc, this object offers only ≈ 0.1 the path length to 3C 273; however, the flux at Earth appears to be 11 times greater than that from 3C 273 in the energy band 1 to 10 keV, and 37 times greater in the 0.25 to 10 keV band if the spectrum of Fritz et al. is correct. This source has the disadvantage of definitely having a photoelectric absorption component due to galactic matter, since it is located at low latitude. However, column densities of hydrogen within the Galaxy may be derived from 21-cm data, and thus the necessary correction can in principle be made with reasonable precision.

There is an existing spectrum of NGC 1275 (Fritz et al., 1971) which has been fitted with a power law spectrum with no turnover when corrected for galactic absorption. However, the published spectrum lacks sufficient detail to subject it to the analysis required to set statistically valid upper limits on the X-ray optical depth. It does appear that this spectrum is not incompatible with the results reported here.

The data on 3C 273 reported here have another interesting implication. It has been shown by Silk (1970) that if all quasi-stellar sources have X-ray luminosities similar to that of 3C 273 and exhibit suitable evolutionary effects, quasars provide sufficient X-ray emission to explain the intensity of the diffuse X-ray background. We note that the similarity of the spectral index derived here for 3C 273 to that of the diffuse background in the 1 to 10 keV band is consistent with this suggestion.

We acknowledge several useful discussions with Dr. J. Silk. This work has been supported in part by NASA Grant NGR 05-003-278.

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Figure Captions

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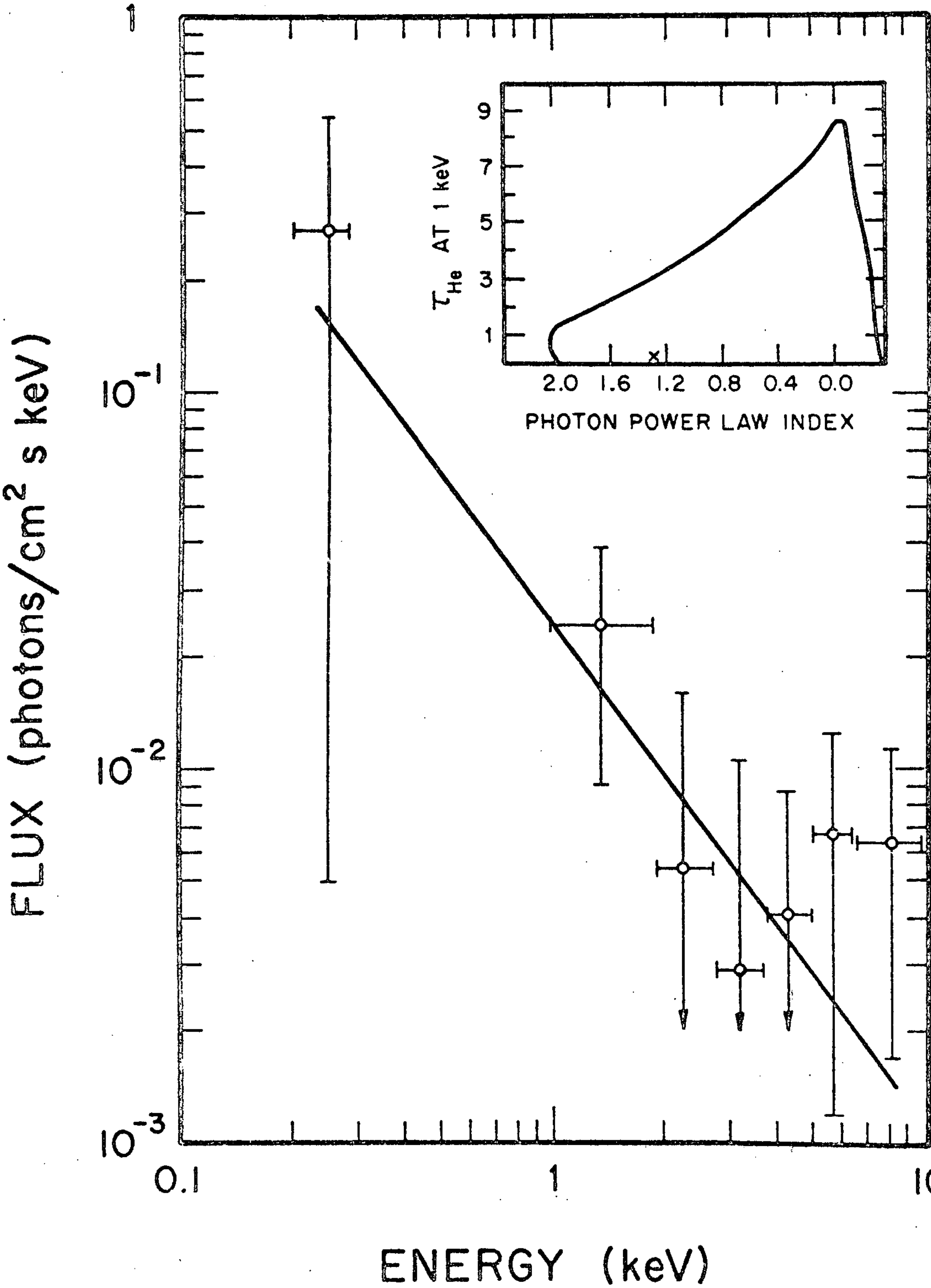
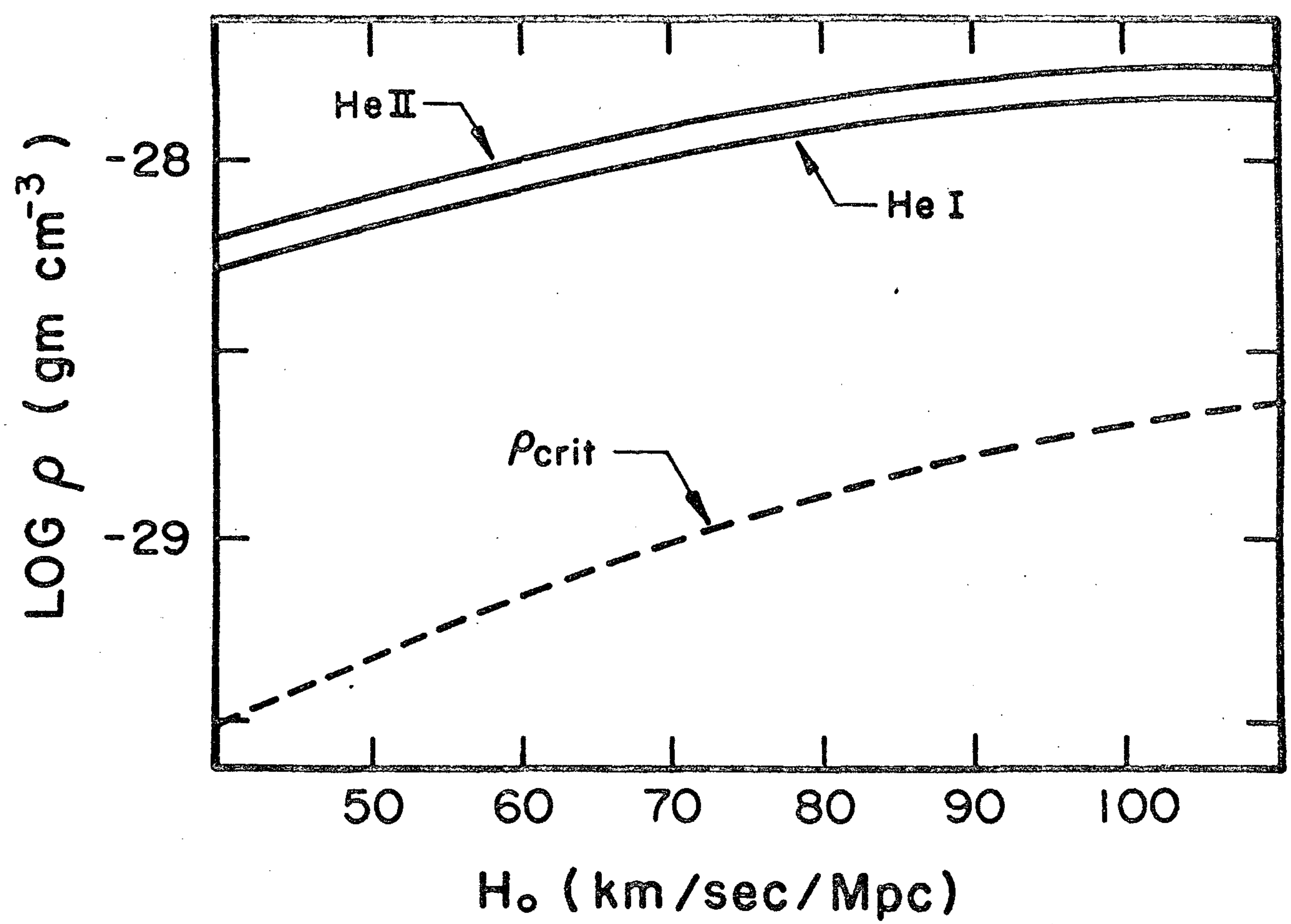


1
10^{-1}
10^{-2}
10^{-3}
FLUX (photons/cm^2 s keV)
0.1
1
10
ENERGY (keV)
τ_{He} AT 1 keV
9
7
5
3
1
2.0 1.6 1.2 0.8 0.4 0.0
PHOTON POWER LAW INDEX

Fig. 1
Margon



He II
He I
ρ_{crit}
-28
-29
50
60
70
80
90
100
LOG ρ (gm cm^{-3})
H_o (km/sec/Mpc)

Fig. 2
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